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HIGH ENERGY PULSE FAILURE OF WIRE-WOUND RESISTORS

Clarkson College of Technology
Potsdam, NY 13676

November 1976

Final Report

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Prepared for
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DEFENSE NUCLEAR AGENCY
Washington, DC 20305

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This technical report has been reviewed and is approved for publication.

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Wire-wound resistors subjected to high energy pulses can fail from fracture of the resistor cases or from permanent changes in resistance value. Large changes in resistance value are obtained only from temperatures approaching the melting point of the wire. Based on this fact, good correlation has been obtained between experimentally measured breakdown energies and theoretical energies required to reach the melting temperature.

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CONTENTS

I INTRODUCTION

This paper will describe the results of a theoretical and experimental program to investigate the failure of wire-wound resistors due to high power pulses of short duration. The power-handling capability of electronic components is generally limited by the maximum allowable temperature rise the device is able to withstand. Thus the investigation can be divided into two interrelated phases. First, the maximum allowable temperature which produces permanent changes in resistive value greater than a predetermined tolerance must be ascertained. Second, the temperature distribution produced by a single power pulse must be determined.

Three methods were employed in the investigation of the failure of wire-wound resistors. These were temperature cycling, pulse testing, and computer simulation of the devices. The samples included various diameters of high resistivity nickel-chromium based alloys (Evanohm), low resistivity copper based alloys (Cupron), and commercially manufactured wire-wound resistors. Table I lists the properties of the resistance wires and materials used for the computer simulations.

TABLE I

Properties of Resistance Wire and Resistor Materials.

Material	Specific Heat Joules/gm-°C	Thermal Conductivity Watts/cm-°C	Density gm/cm^3	Melting Point °C
Evanohm	0.448	0.152	8.1	1350
Cupron	0.393	0.212	8.9	1210
Air	1.00	0.000242	0.001297	
Phenolic	1.03	0.00157	1.62	1635
Silicone Rubber	1.47	0.00243	1.16	936
Silica	1.00	0.0173	1.762	1705
Steatite	0.837	0.021	2.796	1816
Aluminum Oxide	1.00	0.035	3.684	2035
Polyvinyl Formal	0.837	0.001	0.69	

II EXPERIMENTAL

Two experimental tests were performed on samples of resistance wire and wire-wound resistors. These tests included temperature cycling and high energy pulsing. The wire samples were 30 cm lengths of Evanohm (0.36, 0.142, and 0.0254 mm in diameter) and Cupron (0.127 and 0.0279 mm in diameter). The resistors were all 1%, 1 or 2 watts, and consisted of the following: Manufacturer A (16.0, 100, 292, and 1000 ohms), Manufacturer B (20.0, 200, and 470 ohms), Manufacturer C (0.50, 3.00, 51.0, and 13,000 ohms for temperature cycling; 15.2, 200, 820, and 3,000 ohms for pulse testing).

The temperature cycling tests were performed in the following manner.

1. Using a precision resistance bridge, the sample was measured at room temperature.

2. The sample was then placed in an oven preheated to a selected temperature. After a sufficient time to reach equilibrium the sample was measured again.

3. The device was then cooled to room temperature and measured again.

4. The process was repeated at a still higher temperature.

Wire samples were heated to 1100°C. Resistors were limited to a maximum of 350°C. Above this temperature the materials comprising the substrates, coatings, and jackets melted or decomposed.

A typical variation in resistance of nickel-chromium alloy wire during temperature cycling is shown in Fig. I. At low temperatures the temperature coefficient is well within the manufacturer's specifications. At higher temperatures the change in resistance is substantially greater, and changes sign several times. With both nickel-chromium alloys and copper based alloys, temperatures close to the melting point must be reached before the resistance changes by 5%.

Since the resistor samples were only cycled to 350°C or less, the changes in resistance were very small, but somewhat larger than the changes measured in the wire samples. The excess changes reflect the annealing of winding stresses and the change in contact resistance between the resistance wire and end caps.

Figure II is a diagram of the high energy pulse test. The trigger generator provides a single-shot, narrow pulse sync signal. The pulse

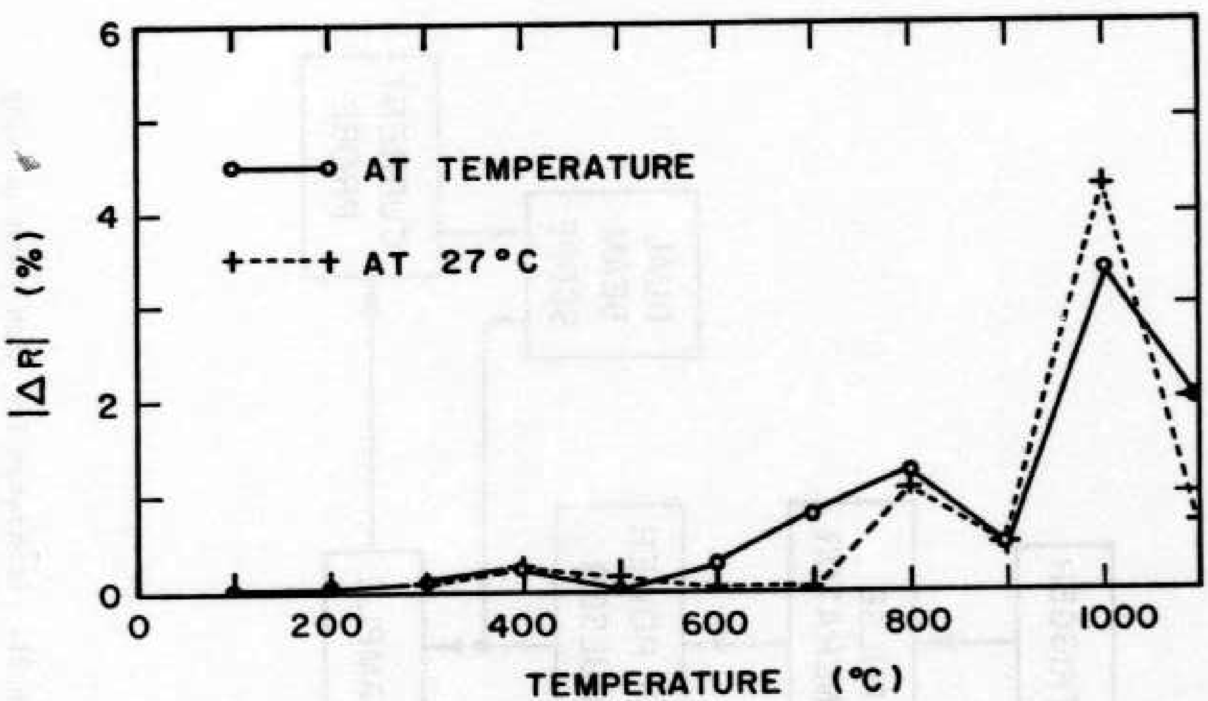

Figure I. Magnitude of resistance change in percent during temperature cycling test for Evanohm wire, 0.0254 mm in diameter.

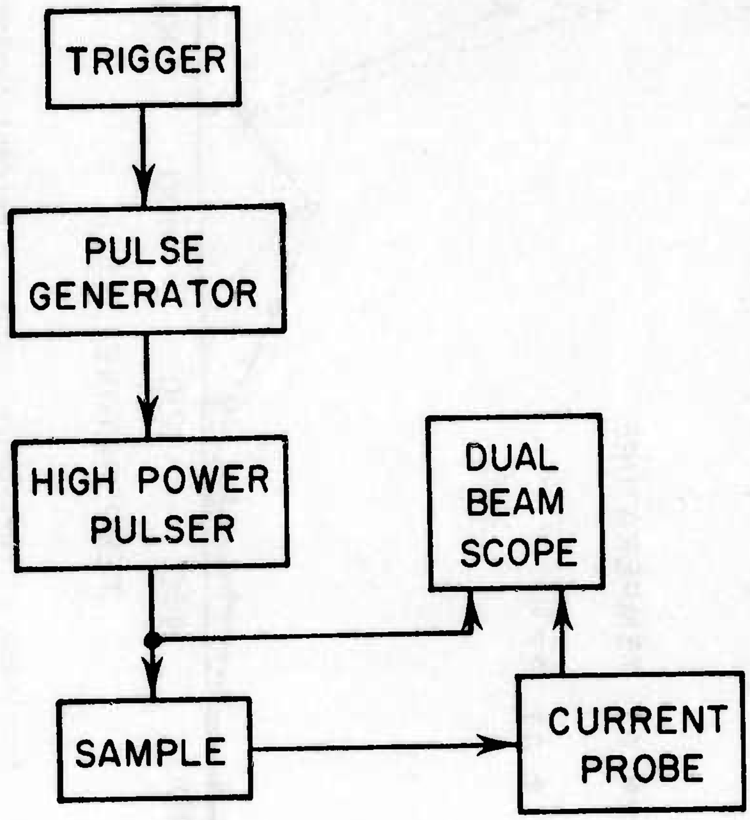

Figure II. Apparatus for high power pulsing. The voltage and current waveforms are recorded on Polaroid film.

2 generator controls the pulse width, and supplies the drive and rise time requirements for the high power pulser. The high power pulser provides a rectangular pulse up to 24 kw in peak power, continuously adjustable in amplitude. Both current and voltage waveshapes are recorded. The procedure for the pulse test was as follows:

1. The resistance of the sample was measured.
2. The device was then subjected to a high energy pulse.
3. The resistance of the sample was measured again.
4. If there was no detectable change in resistance value the amplitude of the pulse was increased and the sample was pulsed again.
5. If the device showed a resistance change a fresh sample was selected and pulsed at a higher level.

An example of pulse testing results is given in Fig. III. This diagram shows the per cent change in resistance as a function of pulse energy. Catastrophic failure implies an open circuit, or a resistance change greater than 100%. Some units failed by a mechanical fracture of the resistor casing, even though the resistance value did not necessarily change. This type of failure occurred only on resistors in which the wire was firmly embedded in a rigid matrix. For windings which were held in place by flexible silicone rubber no such failures occurred.

III COMPUTER SIMULATION OF HIGH ENERGY PULSE BREAKDOWN

For single, high energy pulses, the temperature rise of the resistor wire can be calculated by the adiabatic approximation whenever the heat diffusing away from the wire is small compared to the total energy input. In the adiabatic condition the temperature rise is given by

$$\Delta T = \frac{P\,t}{\rho\,c} \qquad (1)$$

where

ΔT is the change in temperature (°C),

P is the power density (watts/cm^3),

t is the width of the pulse (seconds),

ρ is the density of the wire (gm/cm^3),

and c is the specific heat (joules/gm-°C).

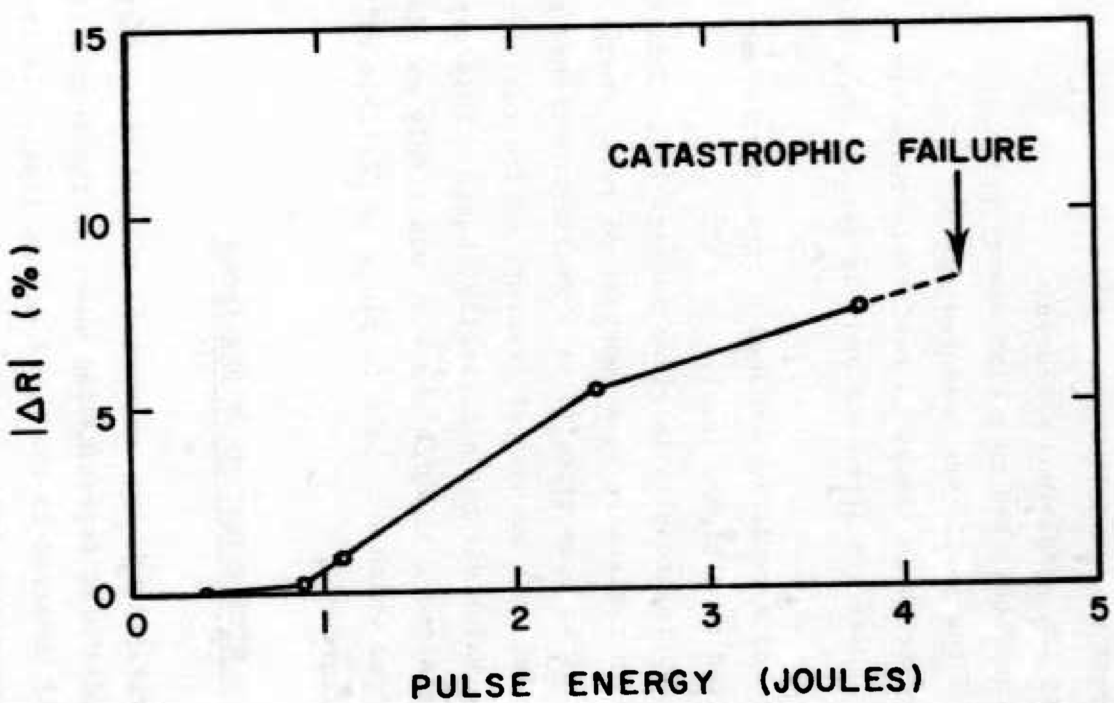

Figure III. Percent change in resistance as a function of energy for a 1.2 msec pulse. Resistor is 20 ohms, wound with 0.089 mm Evanohm wire.

This equation is a good approximation to the temperature rise in many cases, and is an upper limit in all cases.

To investigate heat flow when the adiabatic approximation was not valid, computer solutions to the heat flow problem were used. The computer program employed a finite difference technique to solve for the transient temperature distribution in a model consisting of a resistance wire surrounded by one or more layers of material such as air, varnish, phenolic, silicone rubber, silica, steatite, or alumina. For small wire sizes or long pulse widths these materials can have a significant effect on the temperature rise.

The results show that a wire sample in air is accurately described by the adiabatic approximation for pulse widths used here. In one of the experimental tests Cupron wire 0.0279 mm in diameter was pulsed to catastrophic breakdown, that is, until the wire melted. The required energy was 0.769 Joules. Using Eq. 1, the calculated change in temperature with the appropriate energy density was 1183°C. Assuming the initial temperature was close to room temperature, the final temperature agrees closely with the melting temperature of Cupron, 1210°C. The computer model predicted that the wire would reach its melting point in 81 μsec, very close to the experimentally observed value. Similarly, experimental tests on 0.0254 mm Evanohm showed failure at 0.74 Joules. Equation 1 predicts failure in 283 μsec while the computer program results in failure at 286 μsec. These are very close to the experimental values. Hence there is excellent agreement among the results.

Temperature rise in a real resistor is not necessarily adiabatic, as shown in Table II. This table is a comparison between the energy required for catastrophic failure experimentally and the adiabatic energy required for the wire to reach the melting point as calculated from Eq. 1. The experimental energies are significantly greater, particularly for fine wire, indicating that a substantial amount of heat diffuses into the surrounding material in the 1.2 msec pulse width used.

The temperature distribution in a 0.0254 mm Evanohm wire with 0.00635 mm of varnish and imbedded in steatite was obtained from the computer and is plotted in Fig. IV for t = 31 μsec and t = 76 μsec. Also shown is the temperature rise for adiabatic heating. The power density is the same as in the example discussed above. The deviation from pure adiabatic conditions is readily apparent even at these short time intervals.

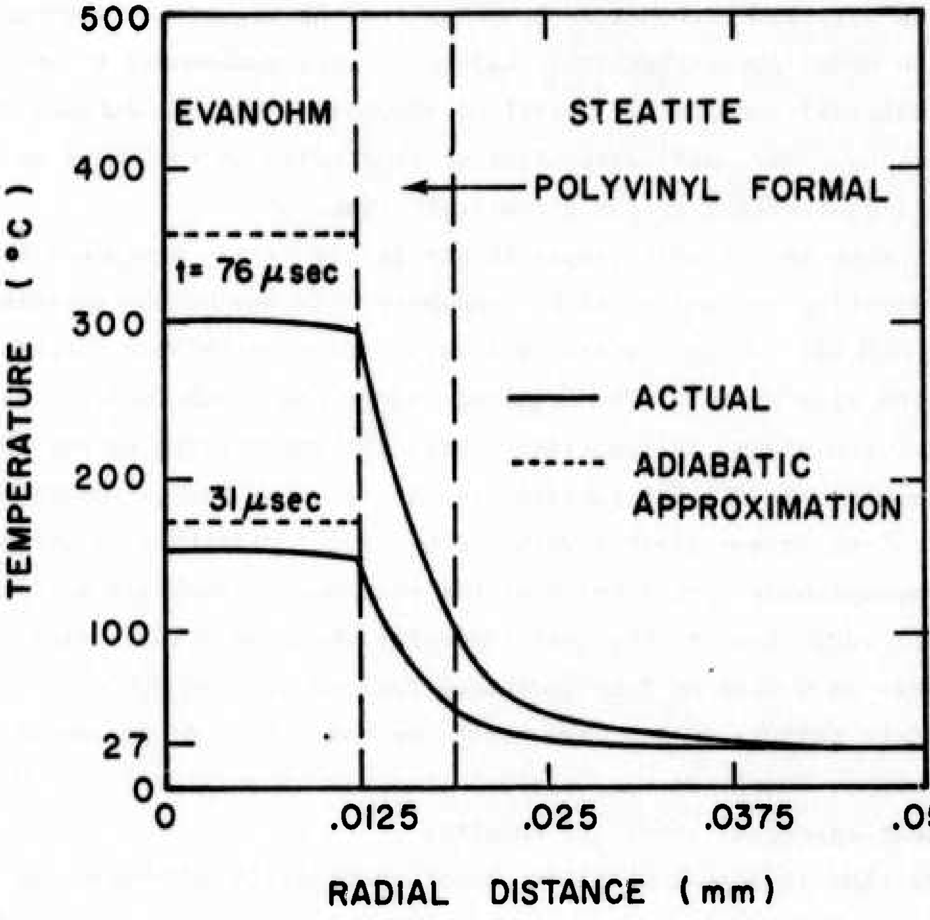

Figure IV. Temperature distribution in a varnish-coated Evanohm wire imbedded in steatite. Power density is 1.7×10^7 watts/cm^3.

TABLE II

Breakdown Energy for Wire-Wound Resistors from Manufacturer B. Pulse Width was 1.2 msec.

Resistance	Wire Diameter (mm)	Energy (Joules) Adiabatic	Experimental
20Ω, 1W	0.0787	2.181	2.872
200Ω, 1W	0.0381	0.930	1.506
470Ω, 1W	0.0305	0.895	2.046
20Ω, 2W	0.0889	2.780	4.068
200Ω, 2W	0.0445	1.732	2.916
470Ω, 2W	0.0381	2.202	3.923

The time required to reach breakdown for the same power density used in the two examples was calculated for a variety of coating materials. The results are summarized in Table III. The presence of any coating increases the time to breakdown over that of a bare wire in air. When the wire is enameled, the effect on breakdown time depends on the thermal properties of the outer layer. If the third coating has good thermal properties, the enamel acts as an insulator and decreases the time to breakdown. If the outer coating has poor thermal properties, the enamel itself acts as a heatsink and increases the breakdown time.

Figure V shows how the coatings affect the continuous rise in temperature. All coatings (except air) lower the wire temperature to some extent. Even for the shortest time periods shown in the figure there is some heatsinking effect. The wire has such a small diameter that heat diffuses away quickly and adiabatic conditions do not hold.

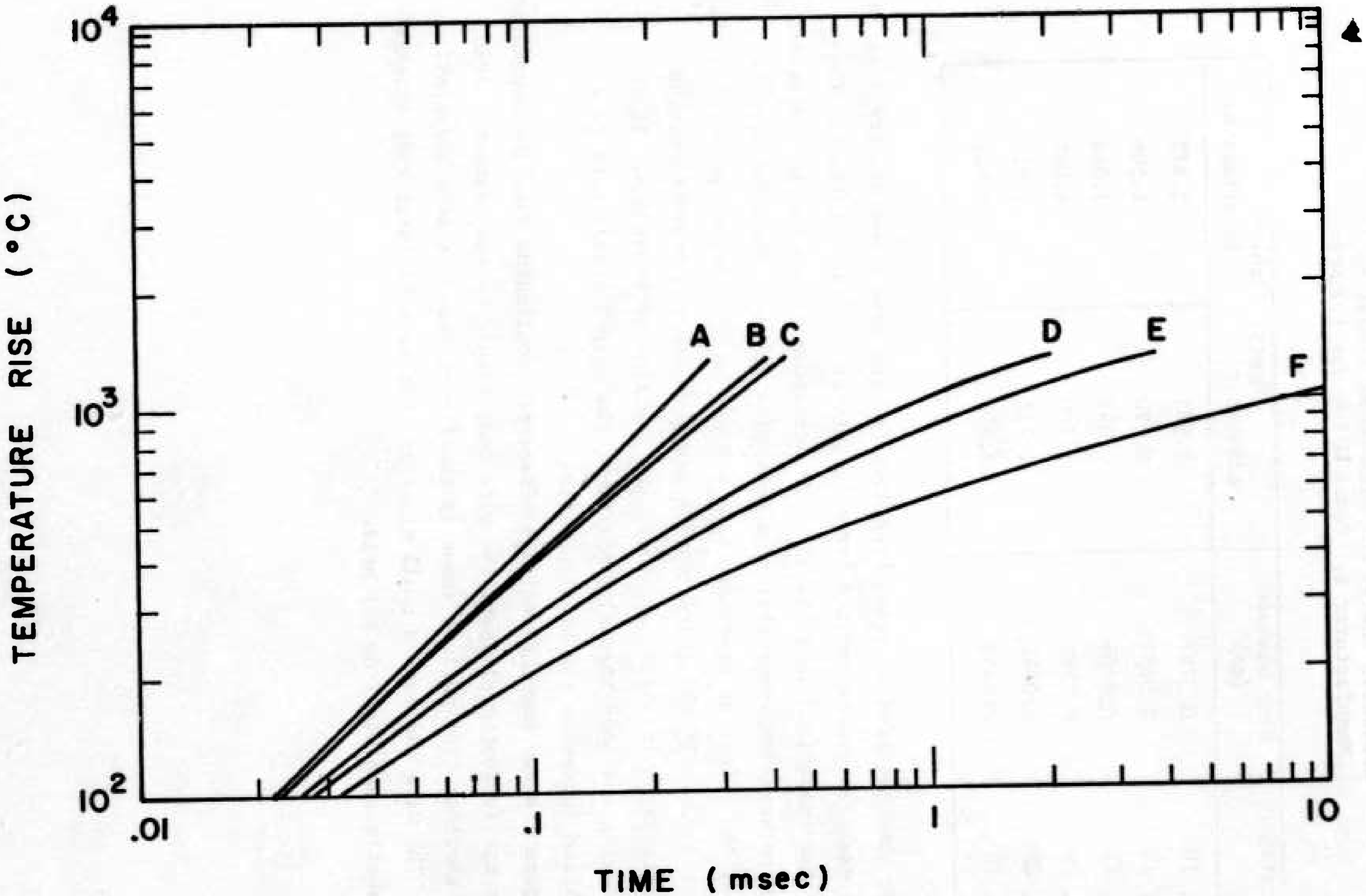

Figure V. Temperature rise in a 0.0254 mm Evanohm wire with various coatings. A (air), B (phenolic), C (silicone rubber), D (silica), E (steatite), F (alumina). Power density is 1.7×10^7 watts/cm^3.

TABLE III

Computer Calculations of Resistor Breakdown.

Evanohm (0.0254 mm) $P = 1.7 \times 10^7$ watts/cm^3			Cupron (0.0279 mm) $P = 5.2 \times 10^7$ watts/cm^3	
Time No Enamel	Time With Enamel	Material	Time No Enamel	Time With Enamel
285 μsec	340 μsec	Air (Adiabatic)	80 μsec	93 μsec
391 μsec	464 μsec	Phenolic	92 μsec	100 μsec
433 μsec	503 μsec	Silicon Rubber	96 μsec	102 μsec
2.90 msec	1.21 msec	Silica	145 μsec	111 μsec
3.90 msec	1.741 msec	Steatite	149 μsec	113 μsec
17.0 msec	6.35 msec	Aluminum Oxide	302 μsec	116 μsec

IV CONCLUSIONS

The ability of wire-wound resistors to handle high energy pulses is limited by the maximum temperature rise of the resistor. Failure can occur in either of two modes; either the resistor value changes beyond some predetermined limit (5% was used in this study), or the casing ruptures, causing an environmental failure. In the second type of failure the resistance value may still be within specification.

The two methods for determining failure of resistance wires and commercial resistors were temperature cycling and pulse testing. The temperature cycling tests showed that temperatures close to the melting point of the wire must be reached before 5% changes in resistance value occur. In commercial resistors the resistance change was somewhat greater due to changes in winding stresses and changes in intermetallic resistance where the wire is bonded to the endcaps. This was borne out in the pulse tests where resistors often experienced more than a 5% change in value before wire melting occurred.

The pulse tests also indicated that the energy for resistor failure is substantially greater than that predicted from adiabatic heating of the wire. Computer calculations revealed the effects of surrounding materials on the temperature rise of the wire and showed how the breakdown time was increased.

The thermal-conductivity-density-specific heat product of the material surrounding the wire is a good measure of the ability to withstand high energy pulses. As the $k\rho c$ product increases, the time for resistor breakdown also increases. The minimum amount of pulse energy for breakdown can be calculated from Eq. 1, and by adding coating materials the threshold energy for breakdown will increase. Hence if the wire type and size used in a particular resistor can be determined, Eq. 1 will give a conservative estimate of the breakdown energy.

The primary characteristic of a resistor which is about to fail is a steady increase in resistance value with increase in pulse energy. Since precision wire-wound resistors are usually constructed with longer lengths of heavier wire than comparable power wire-wounds, they are inherently capable of withstanding higher pulse energies with less change in resistance.

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